Development of a CO_2 laser machine for pulling and welding of silica fibres and ribbons

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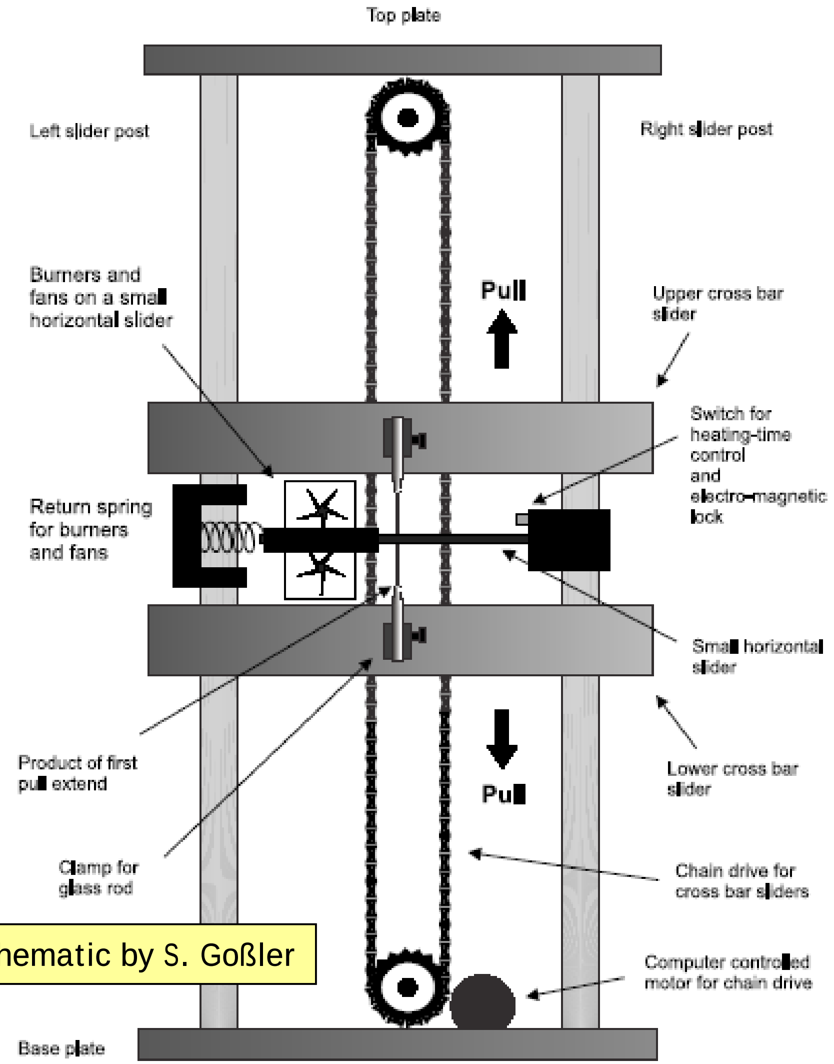
GEO 600 silica suspension fibres – fabrication & welding technique

- Circular fibres pulled using oxy-hydrogen flame pulling machine designed in Glasgow. Manual flame welding.
- Successfully installed in GEO 600 in 2002.
- Limitations
  - Conductive/convective heating
    - Vaporisation of material on outer surface
    - Surface defects/contamination by combustion products can limit strength
  - Shape control - limited
    - Unsophisticated - melt and pull before silica cools down
  - Reproducibility - limited
    - Uniformity of cross sectional area at ~ 10% level in GEO 600

VIDEO CLIP OF FLAME PULLING OF RIBBON by A. Heptonstall (see Glasgow SUS CO2 Development web page)



schematic by S. Goßler

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Improved silica fibre technology for advanced room temperature detectors

- Advanced detectors require higher specification fibres than GEO 600 – must push silica technology to the limit at room temperatures e.g. Advanced LIGO baseline is to use ribbons (thinner, more compliant, higher dilution factors)

- Use CO_2 laser machine for pulling & welding of fibres/ribbons
R & D part funded by EGO organisation and by the UK funding agency PPARC

EGO European Gravitational Observatory
INFN - CNRS Consortium

PPARC

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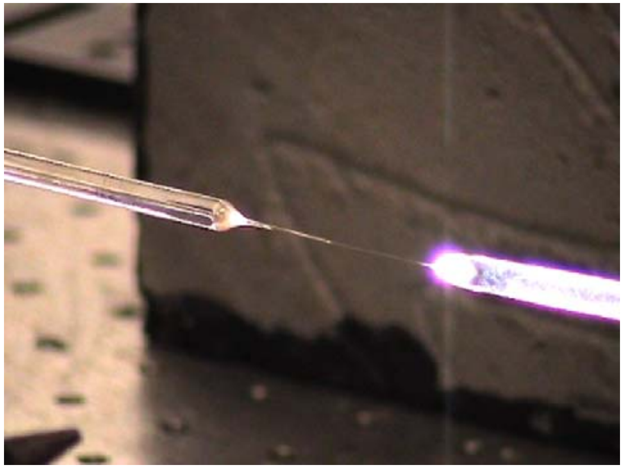
CO_2 laser pulling & welding of silica fibres/ribbons

- Use CO_2 laser radiation (10.6 μm) to melt silica
- Potential advantages of laser fabrication & weld:
  - Very fine control of quantity and localization of heating
  - Reduced contamination
  - Improved shape control by feed & pull (can also be done by flame)
  - Diameter self-regulation effect – possible exploitation
  - Rapid energy control – fibre diameter feedback control possible
  - Re-correction of shape, stress relief/annealing afterwards
  - Precision welding – improved weld shape



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Diameter self-regulation

- Heat gained by absorption ($\propto$ vol) balanced by heat lost by radiation ($\propto$ area)
- As fibre is pulled the surface to volume ratio increases
- Material automatically cools as diameter decreases and pulling will cease
- For a given power of laser and constant axial tension should be able to reproduce fibres of identical diameter
- Question:
  Can this effect be exploited for pulling our advanced fibres?

Absorption depth in fused silica at λ = 10.6 μm

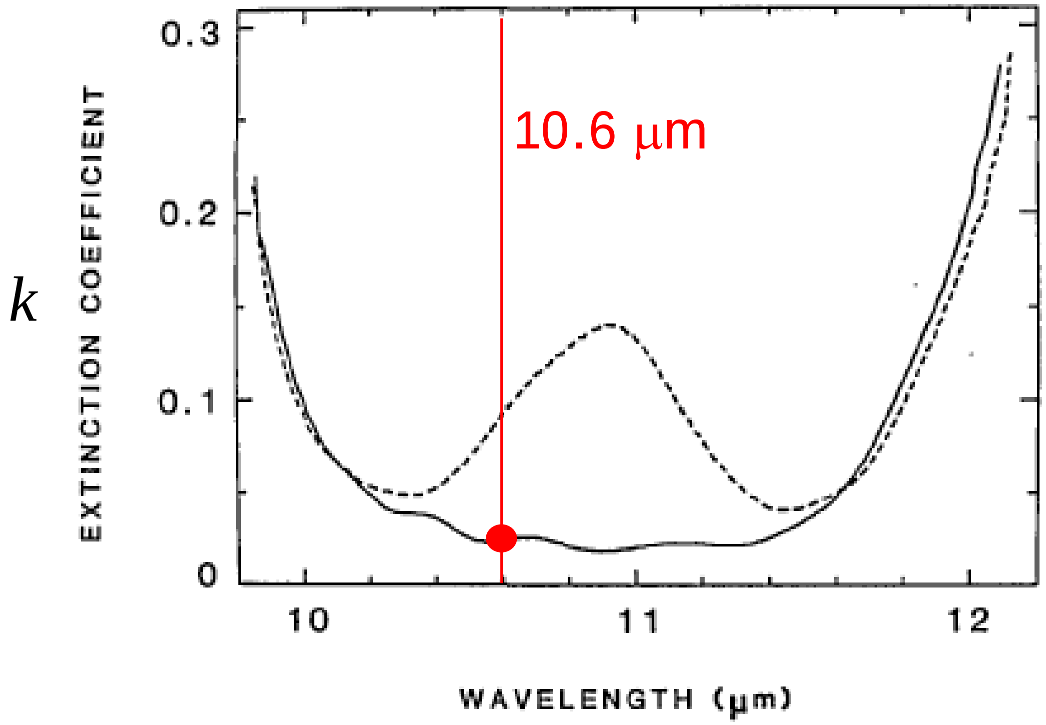

Fig. 3. Values of the extinction coefficient calculated from the data of Fig. 1: ——, pure fused silica; - - -, Vycor. The values were calculated from spectrophotometer transmittance measurements at 25°C.

(M[c]Lachlan & Meyer, Applied Optics, Vol 26 No. 9, 1987)

k = extinction (or attenuation) coefficient

n^* = complex index of refraction

$$n^* = n + ik$$

absorption depth β (intensity reduced to 1/e)

$$\beta = \frac{\lambda}{4\pi k}$$

β = 34 μm at 25°C

Diameter self-regulation: potential for exploitation?

- Question: Can this effect be exploited for our application?

  e.g. Advanced LIGO ribbon dimensions
  600 mm x 1.12 mm x 112 μm

- β only ~ 34 μm at 25°C for 10.6 μm (McLachlan & Meyer 1987)

- Answer: NO, dominated by surface heating and conduction without any substantial absorption of the radiation in the bulk of the material

- Applicable to manufacture of thinner fibres e.g. optical fibres, torsion balance fibres

VIDEO CLIP OF SELF-REGULATION by D.Crooks
(see Glasgow SUS CO2 Development web page)

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Shape control with feed and pull technique

- A key change proposed for advanced pulling process is to use 'feed and pull' technique (established technique).
- Silica stock is fed gradually into the laser beam while fibre is drawn out of the resulting melt. Final fibre diameter given by:

  $(v_{initial}/v_{final}) = (d_{final}/d_{initial})^2$ with v, velocity and d, diameter
- Prototype manual machine has been constructed to test feasibility. Ratio $v_{initial}/v_{final} \sim 1/17$ so diameter of pulled fibre ~1/4 that of stock

first feed & pull jig (manual drive)

250 μm fibre being pulled using feed & pull technique with CO_2 laser

VIDEO CLIP OF MANUAL LASER PULL
by D. Crooks
(see Glasgow SUS CO2 Development web page)

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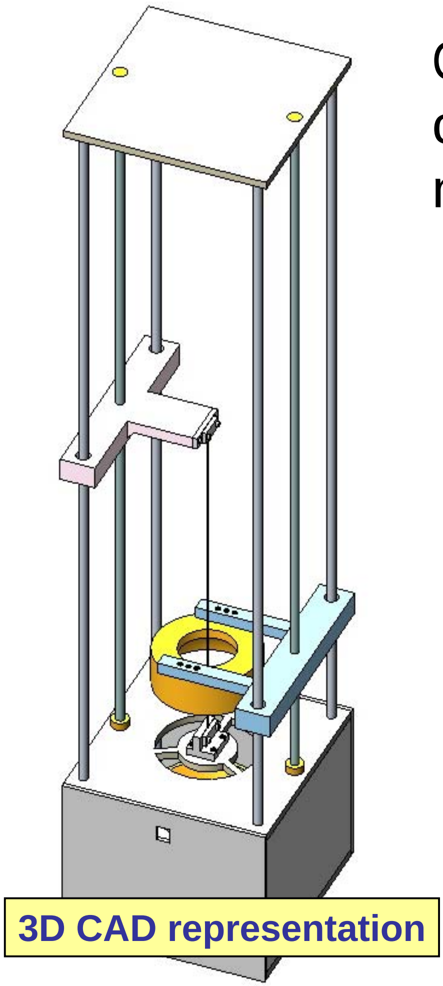
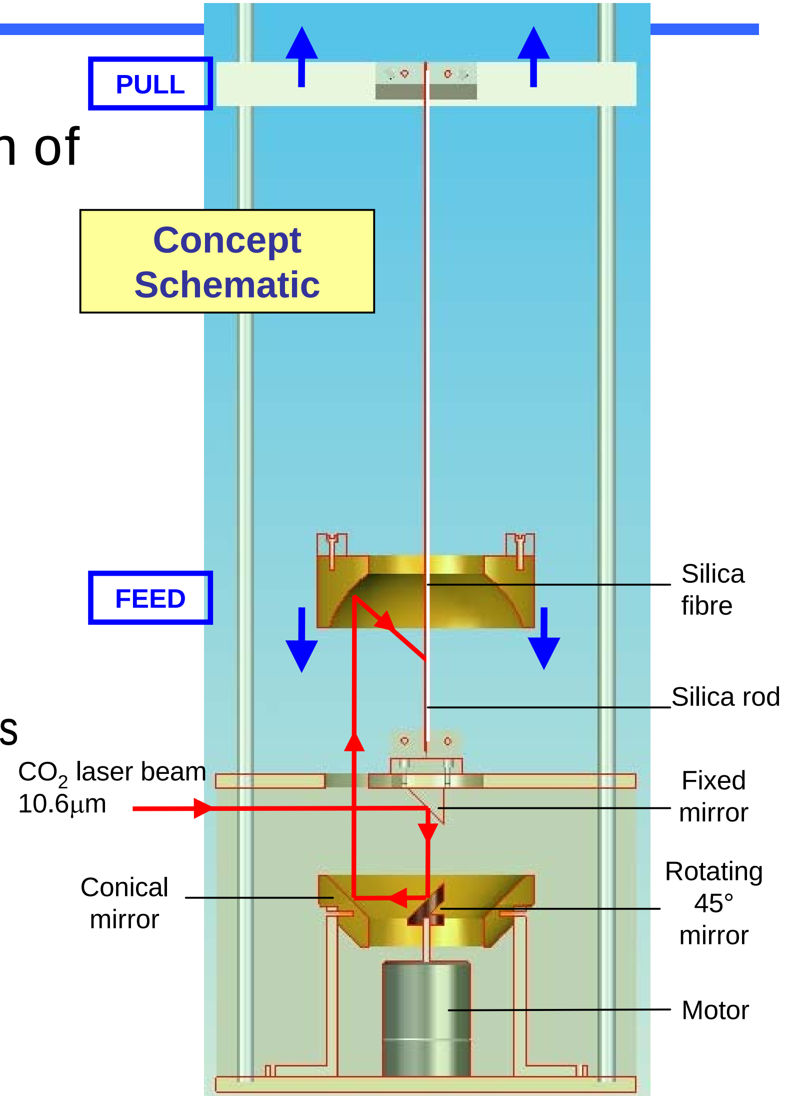
Pulling machine conceptual design



Current conceptual design of cylindrical fibre pulling machine

- fibre stock clamped to base of machine
- focus of laser (ring) moved downwards to progressively melt stock
- upper stock clamp moves upwards to draw fibre
- For ribbons jitter laser beam using 2-mirror galvanometer



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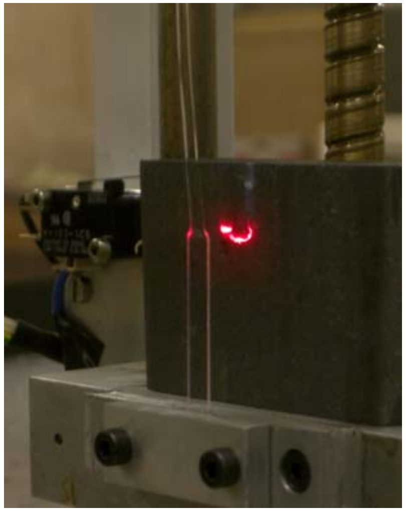
Ribbon manufacture

- Require dual capability machine to produce both fibres and ribbons
- Use single axis mirror galvanometer to jitter beam across surface of rectangular stock using a triangular beam path
  - important not to allow beam to linger on edges of stock (overheating)
  - allow beam to *overscan* the sample
- First test ribbon manufacture promising, strength testing to commence soon



Early demonstration of ribbon being pulled with CO_2 laser

- Gives proof of concept for beam steering in welding context

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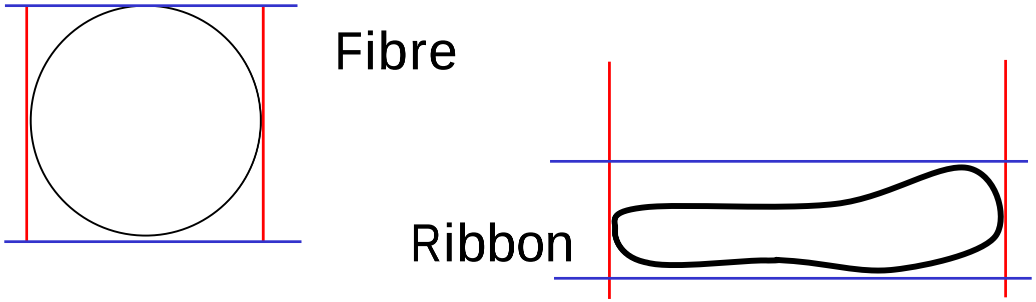
Characterisation

- Require to characterise the pulled suspension elements:
  - mechanical dissipation
  - strength
  - resonant frequencies
- Need to develop technique to characterise shape of silica fibre/ribbon
  - offline characterisation
  - potential online control - use to control machine during pull process
  - 3 possible methods
    - edge detection
    - refraction
    - absorption profile

Profiling

- Edge detection
  - Use either shadow sensor, microscope image or camera image to determine edges of element from which width and thickness can be determined. Gives overall dimensions but does not detect inner features.

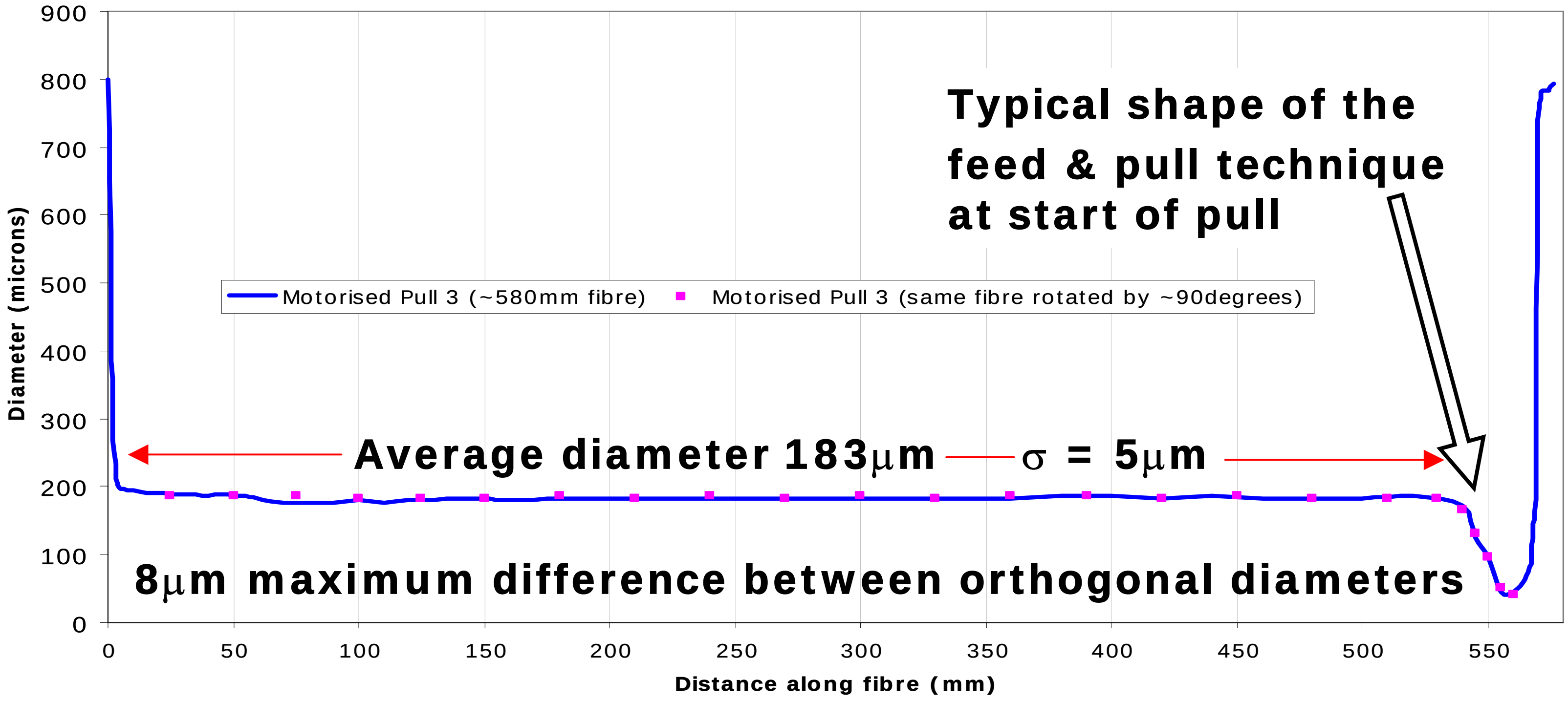


- Refraction
  - Take reference image and use software to determine thickness profile from refracted image
- Absorption profile
  - Use low power CO_2 beam or Beta radiation to scan across element and use absorption to determine thickness
- We are investigating all methods but have focused on edge detection methods to begin with

Typical profile of CO_2 pulled fibre

Fibre pulled using motorised laser jig.

Profiled using (manual) microscope imaging method.



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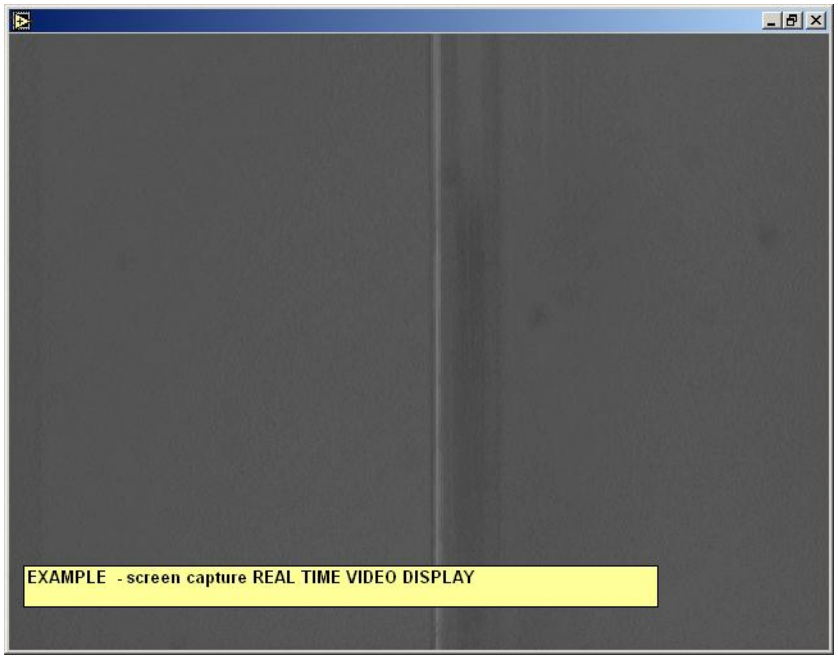
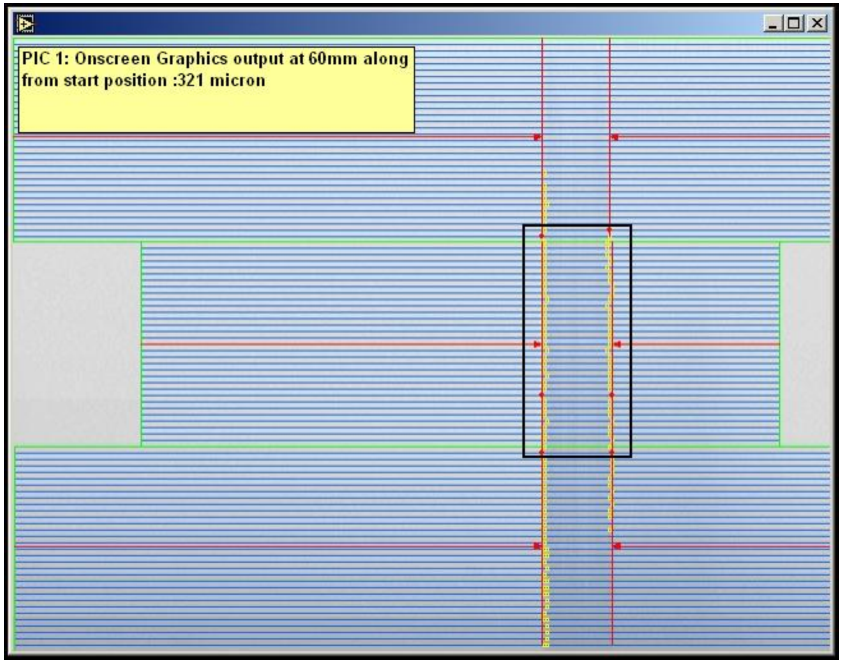
Profiling – edge detection using Machine Vision

- Camera captures image – Machine Vision software automatically determines thickness



screen capture – real time video display



on-screen graphics output

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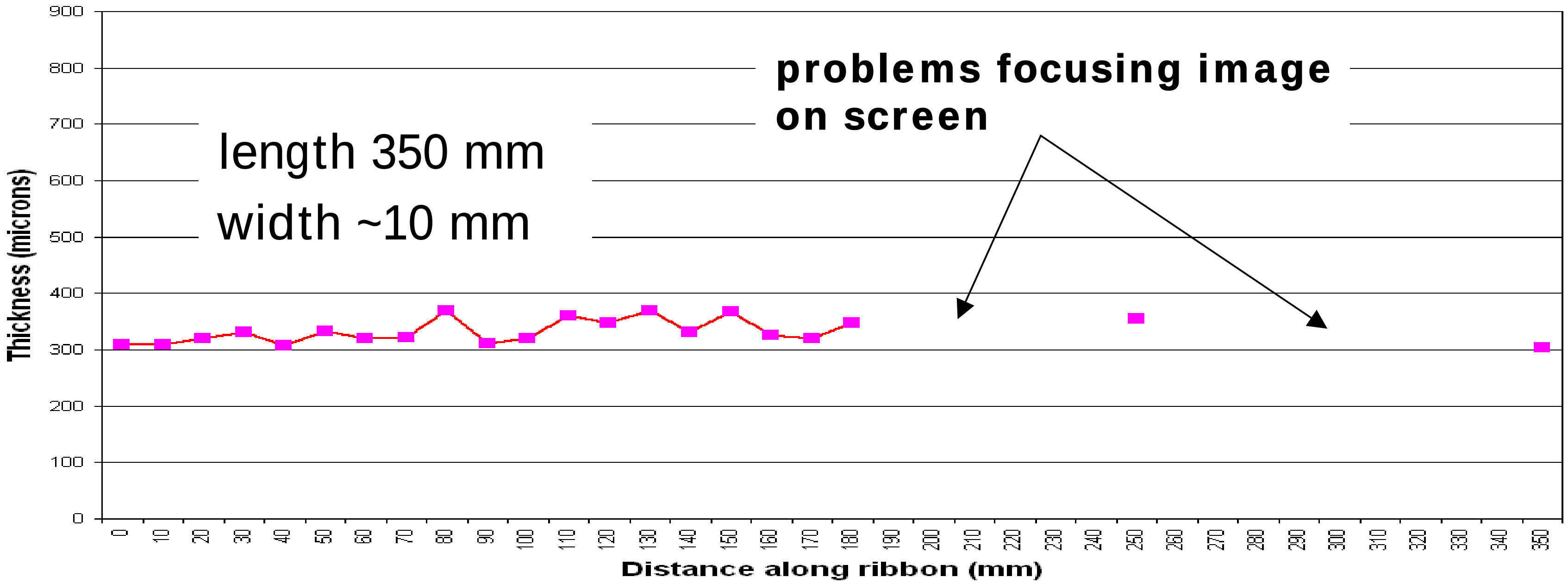
Initial profile of CO_2 pulled ribbon

First profile of laser pulled ribbon using Machine Vision image capture software



Reduce thickness variation by improving uniformity of heating by investigation of optimum jittered beam shape.

Control aspect ratio by implementing variable feed-pull.

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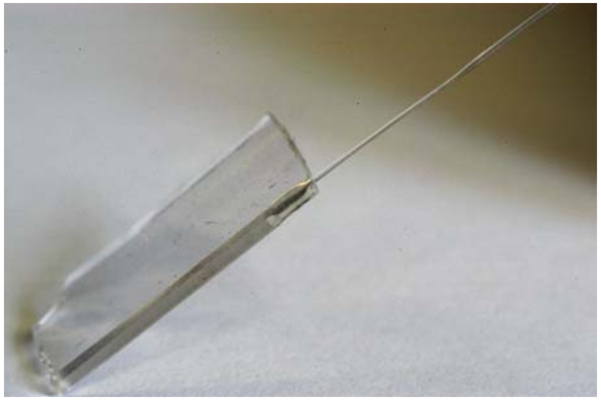
Preliminary strength tests

- Strength testing on fibres
  - fibres will break at the thinnest (or weakest) point
    - breaking stress of 3 GPa already demonstrated for silica fibres
    - validation of laser pulled fibre strength requires improved clamping method due to problem of thinning of neck
- Strength testing on fibre welds
  - ~ 500 MPa breaking stress measured
  - failure close to weld
  - investigations in progress
    - video capture of failure being set-up
  - effect of annealing to be investigated



Example of laser welded silica fibre

Future work

- Variable feed-pull ratio will be implemented in test jig for improved shape control
- Optimum jittered beam shape will be investigated for ribbon pulling
- Fully automated welding technique will be developed
- Profiling methods will be extended
- Ribbon loss measurements have just started and will continue – limited data so far - no firm conclusions yet
- Ongoing characterisation programme for both ribbons and fibres
  - shape
  - breaking stress
  - losses

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